Investigation of a Photoconductively Switched, Radial Transmission Line Accelerator*

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Abstract

This paper analyzes the use of GaAs photoconductive switches and a 2 m radius, radial transmission line section to generate acceleration gradients of up to 50 MV/m for nanosecond duration, 4 kA beam current pulses. The proposed acceleration system is much simpler and easier to precisely synchronize than the annular electron beam "wake field" accelerator designs proposed elsewhere. The design of an accelerator module with annular Blumlein line pulse generator, GaAs switches and associated optical systems, ferrite isolation of the backward wave, and solid state optical control , is presented. In addition, the radial wave equations are solved using the Method of Characteristics and computer solutions compared with experimental voltage amplification data from a 4 m diameter radial line fabricated at UT Arlington. A system point design is presented to indicate the parameters of the component requirements and the system performance parameters.

I. Photo-Switched Radial Line Accelerator System

The ideal power conditioning system for a particle accelerator system would generate the desired pulse shape with a switch that operates at relatively low voltages (electric fields) and deliver the largest possible voltage or electric field pulse to the acceleration gap. Presently, flashover of the vacuum side of the insulator separating the power system from the beam channel limits the acceleration gradient to about 100 kV/cm. In addition, higher electric field pulses can be applied to a vacuum acceleration gap if the pulse duration is shorter than the vacuum breakdown time. Therefore, an ideal accelerator power system would deliver a high voltage (electric field) pulse whose duration is less than the vacuum breakdown characteristic time to a vacuum acceleration gap geometry that is not supported by material surfaces.

The photoconductively switched radial line accelerator power system is comparable to the "wake field" accelerator concept [1], but uses photoconductive switches to generate a precisely synchronized radially converging wavefront instead of a relativistic, annular electron beam. The photoconductively switched, radial line transformer system has the characteristics of an ideal accelerator power system mentioned above.

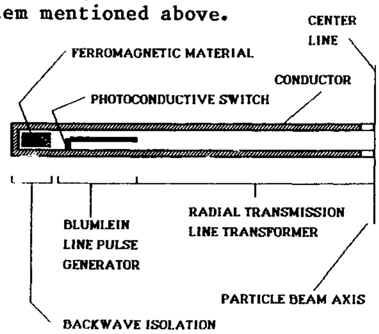

Figure 1. Photoconductively Switched Radial Transmission Line Accelerator Cell

A single accelerator cell, shown in Fig. 1, consist of four parts, (1) a radial line transformer, (2) a photoconductively switched, annular Blumlein line pulse generator, (3) a ferromagnetic backwave isolator section, and (4) an optical switch control system. For the purposes of this paper, the auxiliary systems for magnetic focusing, vacuum, cooling, and etc. will be neglected in order to determine the performance potential of this type of system.

II. Radial Line Transformer

The radial line acts as a frequency dependent transformer which will transform a low voltage or electric field pulse injected at the outside radius into a large electric field pulse at the inside radius of the line. The radial transmission line (RTL), illustrated in Fig. 2, is a nonuniform line due to the

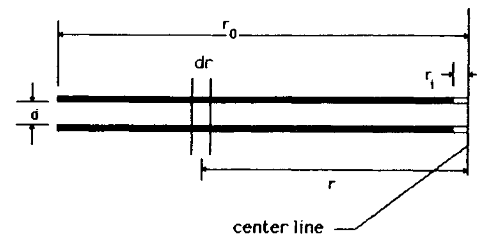

Figure 2. RTL Dimensional Schematic

fact that its inductance and capacitance per unit radial length varies with radial position. The radial variation of the RTL line impedance causes the RTL to act as a wide band transformer [2-4]. The voltage transformation of the line can be approximated by observing the transmission line equations for a lossless line given by

$$\frac{d^2V}{dr^2} - \frac{1}{L(r)}\frac{d\,L(r)}{dr}\frac{d\,V}{dr} - L(r)\,C(r)\,\frac{d^2V}{dt^2} = 0$$

where L(r) and C(r) are the inductance and capacitance at radial position r of length, dr, of the radial line as given by

$$L(r) = \mu_0\, d\, dr/(2\,\pi\, r)$$

and

$$C(r) = 2\,\pi\, r\, dr\, e_0\,/d$$

where d is the separation of the radial conductors, uo and eo are the permeability and permittivity of free space, respectively. The radial impedance at radius r (see Fig. 2) is given by

$$Z(r) = (\mu_0/e_0)^{1/2}\, d\,/\,(2\,\pi\, r) = Z_0\, d\,/\,(2\,\pi\, r).$$

Since the radial impedance increases as the radius is decreased, the reflection coefficient at radius, r, for a change in radius, dr, R(r,dr), is given by

$$R(r,dr) = (Z(r+dr)-Z(r))\,/\,((Z(r+dr)+Z(r))$$

which reduces to

$$R(r,dr) = dr\,/\,(dr + 2r).$$

For a specific frequency component, if the reflection coefficient changes appreciably over a wavelength, then that component is reflected. If dr is replaced with c/f where c is the speed of light in the dielectric medium (vacuum) and f is the pulse frequency component, then the reflection coefficient is given by

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14. ABSTRACT

This paper analyzes the use of GaAs photoconductive switches and a 2 m radius. radial transmission line section to generate acceleration gradients of up to SO MVIm for nanosecond duration. 4 kA beam current pulses. The proposed acceleration system is much simpler and easier to precisely synchronize than the annular electron beam -wake fieldaccelerator designs proposed elsewhere. The design of an accelerator module with annular B1umlein line pulse generator. GaAs switches and associated optical systems. ferrite isolation of the backward wave. and solid state optical control â¢ is presented. In addition. the radial wave equations are solved using the Method of Characteristics and computer solutions compared with experimental voltage amplification data from a 4 m diameter radial line fabricated at UT Arlington. A system point design is presented to indicate the parameters of the component requirements and the system performance parameters.

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$$R(r,f) = 1 / (1 + 2rf/c) .$$

For the reflection coefficient from the outside to the inside of the RTL to be negligible for a minimum frequency, f_m, then

$$2r_i f_m >> c \quad \text{or} \quad f_m = n\, c /(2\, r_i)$$

where n is a multiplying factor. Thus for an inside radius of 0.5 cm, the lowest frequency that is negligibly reflected all the way into the center of the RTL is about 300 GHz when n is equal to 10.

For a sufficiently high frequency, reflection can be neglected and the maximum voltage amplification ratio can be determined by assuming a lossless line and conservation of energy to be

$$V(r_i) = V(r_o)\, (r_o/r_i)^{1/2}$$

where r_o and r_i are the outside and inside radii respectively. Similarly, the ideal current transformation ratio is given by

$$I(r_i) = I(r_o)\, (r_i/r_o)^{1/2} .$$

Note that for sufficiently high frequencies, power is conserved, i.e. $P(r_o) = P(r_i)$. The results of this analysis are similar to earlier work by Prestwich, et.al. at Sandia on the Radlac project.[6]

The radial line geometry and the radial position dependent voltage provides a method of overcoming the present acceleration gradient limit that is due to insulator surface flashover in a vacuum. The radial line conductors can be oriented vertically and the structural supports and insulators located in the regions of low field/voltage. The center of the radial line or the accelerating gap, where the transformed high voltage pulse appears, can be supported in a vacuum without insulating material surfaces bridging the acceleration gap in the presence of the large accelerating field.

III. Photoconductively Switched Annular Blumlein Line Pulse Generator

In order to use the radial voltage/electric field transformation properties of the radial line, an electric field wavefront with a risetime much less than the radial line transit time must be injected at each radial position with a jitter or simultaneity of much less than the pulse duration. Successive accelerator modules must also be synchronized with sub-nS accuracy. In addition, because only the higher frequencies are not reflected, the injected pulse must be short duration (wide bandwith) with minimum rise and fall times requiring a switch with very fast closure times and a very small inductance to permit the low impedance circuit at the outside radius of the radial line to generate the fast risetime pulses.

Conventional switches such as sparkgaps, thyratrons, etc. cannot be realistically employed to meet the simultaneous requirements of sub-ns closure, sub-nH inductance, and sub-ns relative jitter described above.

Photoconductive switches [7] can be designed to switch very large powers with sub-nH inductances, sub-ns closure and resistive times, and be precisely synchronized within ten's of picoseconds. Thus photoconductive power switches (PCPSs) are the enabling technology that make this system feasible.

The Blumlein line pulse generator, illustrated in Fig. 1, was selected for the pulse generation circuit because it provides the maximum amplitude voltage/electric field wavefront into the outside of the radial line impedance with minimum switch voltage requirements and it is geometrically advantageous. The Blumlein structure is switched with an annular array of photoconductive switches as illustrated in Fig. 1.

The radial length of the Blumlein line is equal to half the output pulse length. The impedance of each of the Blumlein lines is given by

$$Z_b = Z(r_o)/2 = Z_o\, (d/2) / (2\, \pi\, r_o)$$

and the maximum switch current is given by

$$I_s = V_c/Z_b = V_c\, 4\, \pi\, r_o / (Z_o\, d)$$

where V_c is the charge voltage and is equal to the output voltage.

The duration of the acceleration pulse is limited by frequency dependent reflection coefficient considerations discussed previously. The pulse rise-time should be a fraction of the pulse duration, or

$$T_r = 0.1\, T_p = 0.1\, r_i/(a\, c)$$

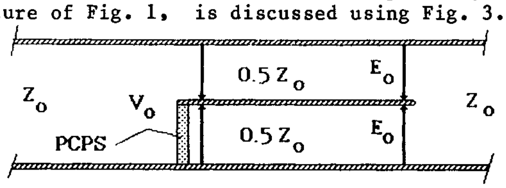
where a is a multiplicative coefficient equal to 10 and c is the speed of light in the RTL vacuum dielectric. This restriction limits the inductance of the annular switch array to

$$L_s <= 0.33\, Z(r_o)\, T_r .$$

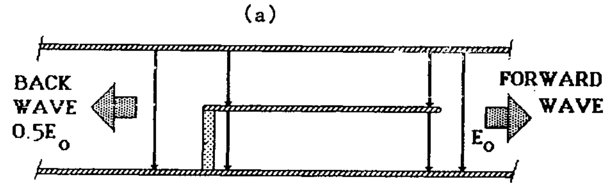
The conduction resistance of the photoconductive switch should be 1 percent of the circuit impedance to insure efficient pulse generation.

IV. Backwave isolation system

The operation of the Blumlein pulse generation structure of Fig. 1, is discussed using Fig. 3. When



(a)



(b)

Figure 3. Backwave isolation structure

the photoconductive switch is closed, a forward wave is launched radially inward. The potential at the top conductor of Fig. 3 on the inside of the radial transmission line system rises to the radially inward pulse voltage when measured with respect to ground. Simultaneously, a radially outward or backward traveling wavefront moves to the left in Fig. 3a. If the structure is not closed, the backwave will exit the radial transmission line structure to produce a potential difference between the top conductor and ground external to the radial line interior. A particle accelerated from the ground electrode to the high potential electrode will eventually be deaccelerated by the backward wave potential which is of the opposite polarity and appears from the top conductor to ground and no net acceleration is possible. However, if the backward wave electromagnetic fields can be confined inside the radial line structure as illustrated in Fig. 3b, the particle beam pulse will be accelerated by only the radially inward traveling potential wave and a net acceleration will be accomplished.

When the backward wave is enclosed, i.e. the top RTL conductor is electrically connected to the bottom

RTL conductor of the radial line as in Fig. 3b, the backward wave sees a very low impedance or short. Therefore, the backward wave region is filled with a high permeability ferrite material such that the impedance of the shorted, radially outward line section is much larger than the line impedance. In this manner the backward wave fields are confined, but minimal energy is lost because of the large ferromagnetic wave impedance. Note that the backward wave, ferrite filled enclosure as illustrated in Fig. 3b, appears as an inductor in parallel with the beam load. In this sense, this accelerator cell is an induction accelerator, but the ferrite is not used to couple the electromagnetic energy to the particle beam. The major advantage in enclosing the backward wave fields is that the exterior of the accelerator cell remains at ground potential and many cells can be placed in series to increase the particle beam energy without cell to cell coupling. The Blumlein structure of Fig. 3 can be operated in several modes. If the photoconductive switch is closed for the two way transit time of the Blumlein structure, the output pulse is determined by the Blumlein line length. However, if the photoconductive switch is closed for only a fraction of the Blumlein line transit time, i.e. by using a much shorter laser pulse, a standing wave of very short pulses can be generated in the Blumlein line, and applied to the RTL input. Because of the very short pulse requirements for taking advantage of the RTL voltage transformation, the second mode of operation may be best.

V. Optical control energy system

The optical energy required to close the photoconductive switch is routed to the switch using optical fibers and waveguide below cutoff structures as illustrated in Fig. 4. In this manner, the optical

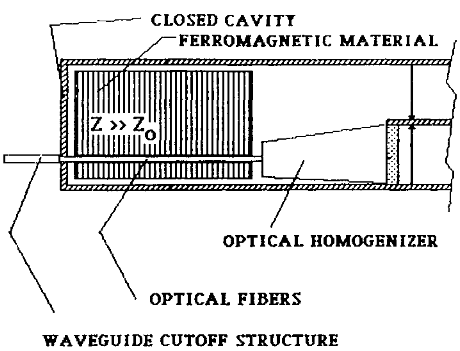


Figure 4. Optical Energy Transport System

wave energy is transported into the back wave region without permitting the back wave fields to leak out.

The optical energy required for switch closure is given by

$$E_L = h^2 E_w /(u_c e (1-r_s) R_c)$$

where h is the switch height and equal to d/2, E_w is the optical control energy wavelength, u_c is the sum of the carrier mobilities in the semiconductor switch, e is the electron charge, r_s is the switch surface reflectivity, and R_c is the desired switch conduction resistance. The optical energy must be delivered in the desired switch closure time so that the peak optical power is given by

$$P_L = E_L/T_r .$$

VI. Low Voltage RTL experiments

A low voltage RTL having an outer radius of 1.8 m and a one way transit time of 10 ns was fabricated and diagnosed to investigate the transformer properties of the line and verify the accuracy of the computer model. The line was fabricated of .050 inch thick copper plates separated by 0.25 inch thick sheets of polyethylene dielectric. The electrical connection at the inner radius was made with a BNC connector where the impedance was measured as about 30 ohms corresponding to an inner radius of about .008 m. In order to measure the transformation properties of the line , the wave traveling radially in the RTL must be independent of angular direction, i.e. injected simultaneously at each point on the outside circumference. Since the transformation properties of the line are independent of direction, the line was driven from the center and the wave reaching the outside radius monitored. In this mode of operation, the wave reaching the outer radius is attenuated with respect to that injected at the inner radius, but the transformation properties can be determined.

The test circuit is shown in Fig. 5. A 50 ohm

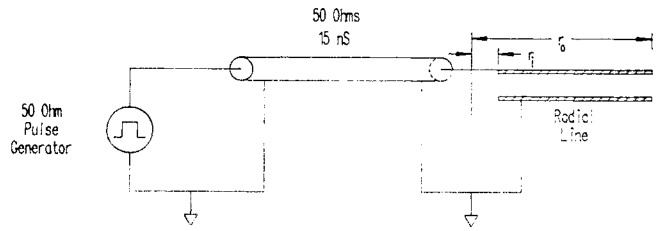
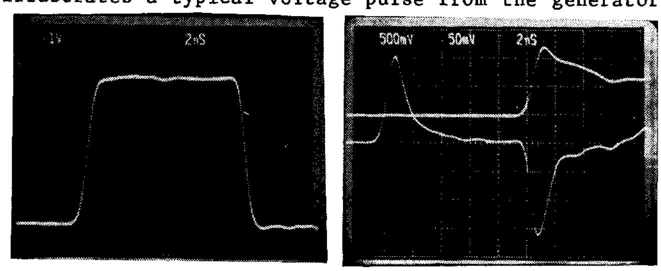


Figure 5. RTL test Circuit

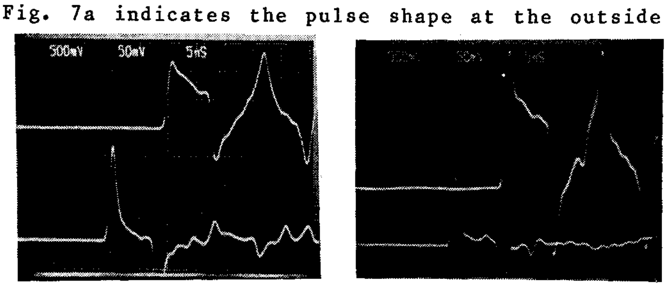
pulse generator with a rise time of one ns was used to drive the center of the RTL through a 50 ohm cable. The cable had a 15ns one way transit time and served to isolate the RTL from the pulse generator. Figure 6a illustrates a typical voltage pulse from the generator



(a) (b)

Figure 6. RTL Input Pulse Voltages

into a matched, 50 ohm load. Figure 6b illustrates how the input pulse is distorted by the time varying impedance of the radial line at the inside radius while Fig. 7a indicates the pulse shape at the outside



(a) (b)

Figure 7. RTL Voltage Transformation Waveforms

radius. The slower risetime (absence of the high frequencies) in the pulse of Fig. 7a is attributed to low frequency response of the measurement geometry at the outside radius. In order to determine if the high frequency components are preserved when the radial line is driven radially inward, the test system was driven at one point on the outside radius and monitored at the center. The results of this measurement are shown in

Fig. 7b, indicating that the high frequency components are preserved and voltage transformed at the inner radius.

VII. Computer Solutions to RTL wave equations

The Method of Characteristics was used to numerically solve the governing equations for the fields in the RTL.[8] The results of the computer model are presented in Fig. 8. Figure 8 illustrates a

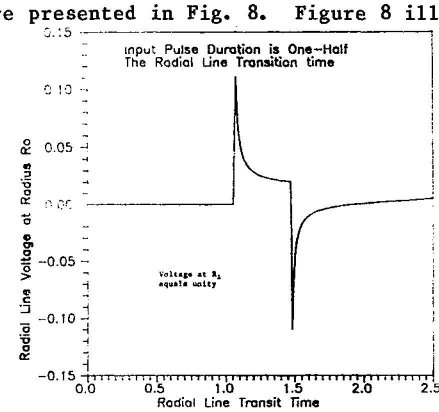


Figure 8. Computer RTL Voltage Transformations

simulation of pulsing the inner radius with a square current pulse at r_i. The outside of the RTL at r_o is an open circuit and the ratio r_o/r_i is 200 to match the experimental conditions. For this particular case, the pulse has zero risetime and the voltage attenuation for the leading edge is $2(r_i/r_o)^{1/2}$ as expected for the open circuit. The computer generated waveforms closely resemble those measured and presented above in temporal and voltage transformation. Thus the method of characteristics is appropriate for predicting the temporal and transformation properties of the RTL.

VIII. System Point Design Parameters

In order to determine the feasibility of a photoconductively switched, radial line accelerator, the first order system parameters discussed above are calculated based on presently available switch technology. The radial line size is chosen to obtain a voltage multiplication factor of 20. The system parameters are listed in TABLE I.

VII. Conclusions

The parameters of the photoconductively switched, radial line accelerator cell listed in TABLE I indicate that this approach can provide very large acceleration gradients (50 MV/m) at appreciable beam currents (4 kA). The first order parameter study described in this paper assumes power and energy conservation for the inward voltage wave, neglects losses due to the backward wave and conductor and switch losses. The pulse duration is restricted to less than one ns in order to take advantage of the voltage amplification properties of the radial line. The optical requirements are well within the state of the art for single or low pulse rate (<10 Hz) operation.

TABLE I
SYSTEM PARAMETERS
PHOTOCONDUCTIVELY SWITCHED RADIAL LINE TRANSFORMER ACCELERATOR

Parameter	Symbol	Unit	Value
OUTSIDE RADIUS	ro	m	2
INSIDE RADIUS	ri	m	0.005
RADIAL LINE SEPARATION	d	m	0.02
FREE SPACE PERMITTIVITY	uo	F/m	8.85E-12
FREE SPACE PERMEABILITY	eo	H/m	1.26E-07
SPEED OF LIGHT	c	m/s	3.00E+08
PI	n		3.1416
FREE SPACE IMPEDANCE	Zo	Ohms	377
IMPEDANCE AT ro	Z(ro)	Ohms	6.00E-01
IMPEDANCE AT ri	Z(ri)	Ohms	2.40E+02
BLUMLEIN CHARGE VOLTAGE	Vc	volts	5.00E+04
SWITCH HEIGHT	h	meters	1.00E-02
SWITCH CURRENT	Is	Amps	1.67E+05
MAXIMUM VOLTAGE AT ri	V(ri)	volts	1.00E+06
MAXIMUM VOLTAGE AT ro	V(ro)	volts	5.00E+04
ELECTRIC FIELD AT ro	E(ro)	volts/m	2.50E+06
ELECTRIC FIELD AT ri	E(ri)	volts/m	5.00E+07
MATCHED BEAM CURRENT	Ib(ri)	Amps	4.17E+03
BEAM PULSE LENGTH	Tp	Seconds	6.65E-10
BEAM CURRENT RISETIME	Tr	Seconds	6.65E-11
SWITCH INDUCTANCE	Ls	Henry	1.32E-11
SWITCH CONDUCTION RESISTANCE	Rc	Ohms	3.00E-03
ELECTRON CHARGE	e	Coulomb	1.60E-19
PHOTON ENERGY	Ew	Joules	1.20E-19
SURFACE REFLECTIVITY	rs		0.3
CARRIER MOBILITY	uc	m2/v-s	0.2
SWITCH OPTICAL ENERGY	EL	Joules	1.79E-01
OPTICAL ENERGY DENSITY	ELd	uJ/cm2	1.42E+00
SWITCH OPTICAL POWER	PL	Watts	2.69E+09
SWITCH POWER DISSIPATION	Ps	Watts	8.33E+07
BEAM OUTPUT POWER	Pb	Watts	4.17E+09
BLUMLEIN INPUT POWER	Pi	Watts	4.17E+09
LASER SYSTEM EFFICIENCY			0.50%
SYSTEM ENERGY EFFICIENCY			7.76%
CHANGE IN BEAM ENERGY		Joules	2.77E+00
OPTICAL ABSORBTION DEPTH	de	m	0.001
SWITCH CURRENT DENSITY	Js	A/cm2	1.33E+03
SWITCH CURRENT/WIDTH	Iw	A/cm	1.33E+02
SWITCH POWER DENSITY	Psd	MW/cm3	6.63E-01

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